TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 206

STRUCTURAL WEIGHT OF AIRCRAFT AS AFFECTED BY THE SYSTEM OF DESIGN.

By Charles Ward Hall.

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Summary

In this technical note various details of design or arrangement of the parts of airplane structures are shown and discussed, the use of these devices having resulted in the production of structures of adequate strength, yet of a weight less than one-half of the usual construction.

Discussion

The structural design of aircraft may be conveniently divided into two general parts: the determination of the loading conditions, and the design of a structure to sustain these loads. It is not the purpose in this note to discuss the first of these divisions, but upon the assumption that a satisfactory specification for each condition of flight or landing is available, to proceed directly to a discussion of some of the available methods of building a structure to sustain these loads with a minimum expenditure of weight.

From one point of view - the pay load - that is, the weight which is to be transported, whether it be mail or other goods, bombs, or machine gun bullets, represents the only profitable part of the enterprise. A minimum weight of airplane structure, a minimum weight of power plant consistent with the necessary performance, a minimum weight of fuel, of lubricant, and of other essential equipment to accomplish with a proper margin the intended voyage, may be considered as detrimental but unavoidably so; in a sense an overhead charge against the enterprise. Anything more than the minimum in these non-profitable loads may reasonably be taken as parasitical and should be eliminated. I shall touch upon only one of the elements of these non-productive loads, that is to say the structural frame of the airplane. This structure may be divided into four general groups:

1. Members subject to tension;
2. Members subject to bending;
3. Members subject to direct compression;
4. Members subject to combined bending and compression.

Tension members are in general very simple in design, and present a problem essentially of quality of material, as the shape is of small consequence, except where exposed to an air flow. The criteria which may be followed in the selection of the most suitable material are the ratios of yield point to density, and of modulus of elasticity to density.

Bending loads without appreciable direct tension or compression occur in various parts of airplanes - such as the wheel axles of land type airplanes and the tail skids.

For axles, the most practical method of keeping down weight lies in the selection of a tube having the best ratio of thickness to diameter for the material used. Frequently the use of wheels having standard hubs limits the maximum diameter of the axle and leaves no option except to select a tube of suitable thickness, in the case of a continuous horizontal axle. This use of standard wheels usually limits the choice of axle material to a heat-treated steel; however, a short section only of such steel tubing may be passed through the wheel hub to form the bearing with its inner end housed into a larger duralumin tube which extends between the landing gear struts - this results sometimes in weight saving. Where the hinged axle is substituted for the straight one the bending moment varies with the distance from the struts; by tapering the thickness of the tube walls, by turning or grinding, there is another means of saving weight, but with the average commercial tubes, due to their lack of straightness and of concentricity there is risk of creating thin walls at some points.

Small tail skids of circular tube may be conveniently proportioned approximately to the bending stresses by the insertion of one or more shorter lengths of tubing therein, so as to afford additional wall thickness at or near the supporting hinge. Duralumin apparently for this use is lighter than steel, and as the air resistance of the airplane is not materially affected thereby, the diameter of the skid may be large enough to permit of the selection of an optimum ratio of thickness to diameter. Of course a steel shoe would be necessary. Shapes other than of hollow circular cross-section may be of advantage in large sizes, and if "built up" may be readily tapered along their length. The principal load on tail skids is vertical, but any side load causes torsional stresses; the cross-section selected should be one having torsional strength, preferably a closed hollow section rather than an I beam, or other open hollow forms.

Compression loads without appreciable bending loads, occur in many different parts of an airplane such as the longerons and struts of a fuselage, the drag struts in thin wings, interplane struts of biplanes, and of some triplanes, tail booms, the web members of trussed type ribs for wings or tail surfaces.

For these members in which direct compression loading predominates, two methods of preventing failure by column action may be used: either the ends of a strut may be more or less fixed by its supports, or the middle of the strut may be stiffened by gradually varying the cross-sectional area so as to diminish it towards the ends. A special case, particularly available for open hollow sections such as angles, consists in gradually varying the width of the flanges while keeping the apex in a straight line. This results in a gradually curved gravity axis of the column, tending, as load is applied, to increase the compression at the apex of the section, and to relieve the edges so that they do not buckle. This is exemplified by the web members of the wing ribs - Fig. 1 - (1) and (2), which, as will be noted, have the least cross-sectional area near the ends, about 90 to 92 per cent as great as near the middle. If such members are of the same cross-section for their whole length they usually fail by buckling or bending of the free edge of one flange near mid length, followed by a sidewise bending of the section. If the thickness is small compared to the width, or diameter, this occurs at a comparatively low stress.

The improved design usually fails by a circular twisting of the entire member, or by bending in such a direction as to put the free edges in tension, with failure occurring at a higher stress. This method of relieving the edges appears to be comparable with the bending and extending of them back to the plane of the neutral axis, as is done for the webs of zeppelin trusses. That adds some 40% of material to the cross-section, whereas the method just described results in the carrying of unit loads equally as great, with about 5% of the material cut away. These ribs also exhibit the use of enlarged fillet ends supporting the web members at their intersections with the chords, at which points the upsetting of the web stock is deep enough to center the web's gravity axis on the chord flange; which arrangement forms a rigid connection between the webs and chords and affords end fixity to both. The chord flanges are reinforced against buckling by occasional ties from one free edge to the other; in a rib such as that illustrated, these ties add 60% to the ultimate strength.

Examples of fittings for fixing the ends of struts which have been employed successfully, are those used in attaching web struts to longerons in fuselage construction - Fig. 2 - (4) and (5). The stays and struts which form the web system of a Warren truss are constructed of tubing, a liner of tubing about three diameters long being first pressed into each end, the tube ends and liners are flattened in a special forming tool which sizes them to a press fit upon the flat lugs of the fitting. The struts are fastened to the lugs by means of two staggered rivets, thus providing a structure which under test developed an end fixity factor in the Euler formula of about 2 for the longerons and 2.15 to 2.89 for the struts. The end fixity of such a longeron is mainly determined by the tightness of the fit in the cylindrical part of the fitting, and secondly, by the length and stiffness of the four stays or struts meeting at any joint. As at least one, and frequently two, of these stays must be under tension, an additional stiffness is afforded to the combination. The end fixity of such struts depends chiefly upon the thickness of the fitting lug, and is therefore very readily computable in usual cases.

Another method of securing end fixity for struts is particularly appropriate to drag struts in wings, or to interplane struts, as it allows riggers to set up the structure, considerably out of line, without straining of the members. The examples of drag struts and their fittings - Fig. 3 - which were used in the HS3 and F4C-1 wings, may readily be turned, as will be noted, upon the ball head bolts, with which they are engaged, and thus adjust themselves to misalignment. . The fitting (9) serves as anchorage for the usual drag wires, and is attached to the spar joint plates by the ball head bolt 12 and nut 13, as shown assembled - Fig. 1 - (3). Fig. 3 - (8) is the end fitting for a large drag strut, the tip of which is spherically hollowed, as is shown in section for the smaller fitting 10. As loading is applied to the structure the ball head of the bolt is pressed into perfect contact with the strut end fitting, and from the resulting friction a fixing moment exists. This fixing moment increases in direct proportion to the end load, and is, in fact, numerically equal to the continued product of the coefficient of static friction, by the radius of curvature, and by the end load. The fixing moment for any end load is thus computed definitely. For the F4C-1 drag strut exhibited (11), which is 5/8" diameter and 25" long, and rests upon a ball head bolt of 3/4" radius, this frictional fixing moment was sufficient to realize a K factor in the Euler formula of 3 to 3.25, the tubing being only commercially straight. This is a higher factor than can usually be obtained by testing with carefully made flat ends. Under loading, such long struts remain practically straight up to the failing load, and when the friction is overcome they jump suddenly to a curved form, and continue to sustain a Euler factor of 1 while so bent. When this load is removed the strut becomes straight and may be reloaded repeatedly with the same result.

Another example of this frictional type of end constraint is the fuselage stay - Fig. 4 - (18) which is provided with end fittings to bear upon the usual clevis pin in connection with such a joint as Fig. 3 - (6) or (7). In this case the diameter of the pin is smaller than the diameter of the tube, and so the fixing moment here is about 1.5 times the Euler round end value, being less than for the drag strut above referred to where the ball radius was larger than the tube diameter.

Vibration, as met with in an airplane, is of a much slower period than the natural period of such struts, and the mass of the struts is so small in comparison to the load sustained, that there appears to be no risk whatever of the frictional bond being broken.

In those members or parts of members which are subject to both bending and compression, such as wing spars, the chords of the truss form wing ribs, the struts of landing gear, etc.; there are available other methods for not only increasing the effective strength of the parts but also for reducing the maxima of the stresses to be sustained. Consider the case of any upper front spar of a biplane under nearly maximum loading, such as occurs in pulling out of a dive. Usually such a spar is designed to be straight between its supports - the interplane struts and lift wires, before the loading. Furthermore, its flanges or chords will usually be of the same cross-sectional area throughout the length of any lift bay. The lift loads transmitted to this spar by the ribs cause it to bend, and if the spar is continuous over several supports, its curvature is sinusoidal, slightly modified by the parabolic deflection of the entire wing truss. Being an upper spar, and under the condition of pulling out of a dive, it is also subject to compressive load, which produced further bending moment, equivalent numerically to the product of the end load by the amount of the deflection from a straight line, and as this deflection at or near the point of failure may be as great as

1" to 2" for a 100" span, it will be appreciated that this bending moment due to end load is large.

If, instead of designing the spar to be straight, it is cambered into a curve of the same form but in a direction opposite to that in which the loading causes it to deflect, then under an increasing load its curvature is gradually decreased until under nearly full load the spar becomes straight. Such an arrangement is shown diagrammatically on Fig. 5 - (1), which represents a biplane in front view. The end moment produces no additional bending moment at mid span because the spar when fully loaded is practically straight between its supports. The deflection due to side loading has been made to assist the spar to resist an end load simultaneously applied instead of adding to the forces which tend towards its failure as a column. In design the cross-sectional area of each chord, of such a cambered spar when suitably restrained by an equivalent of the usual ribs and drag bracing, may safely be proportioned to resist the algebraic sum of the stress maxima produced by the side load, plus the end load considered as uniformly distributed. Cambering a spar having chords of uniform cross-sectional area obviously curves the gravity axis to conform to the curvature of the spar. Another method of accomplishing this same result lies in changing the cross-sectional area of each of the chords of a truss form spar along its length, making the lower chords smaller than the upper over its supports, and the upper chord smaller than the lower over the mid portion between supports. If done in proportion to the variation of the total combined stress along each chord respectively, it will result in a very large saving of weight as compared with the condition in which each chord is designed to carry the maximum stress which occurs only at the most stressed point, and that same cross-section is continued throughout. Furthermore, it results in a curving or camber of the gravity axis of the spar, precisely as was described for the bending of a spar of uniform chord area, to a sinusoidal curve contrary in direction to the load curve. This is shown diagrammatically on Fig. 5 (2). Therefore under bending load the gravity axis tends to become straight, and if the spar has been correctly proportioned it will be quite straight when the loading has reached its intended maximum, and thus the bending moment otherwise due to the product of end load by eccentricity has been eliminated. This it will be noted is accomplished by cutting away unnecessary material.

Practically a combination of these two methods gives the best results, and Fig. 1 (3) shows part of a 100" length of spar originally cambered to about 1/2" with its gravity axis shifted in the direction of camber about 1/2" by making the lower chord of three tubes through the center one-third of its length, and the upper chord of three tubes as the end of the bay is approached, both chords at all other points consisting of two tubes. This section of spar was tested to destruction by applying an end load eccentrically so as to produce an end bending moment, and by also applying simultaneously eight side loads at points equivalent to rib spacing, as shown diagrammatically on Fig. 5 (2). Wires were attached to restrain the spar sidewise at the drag bays, and false ribs were attached to the spar and extended to a parallel bar which represented another spar. The test conditions approximated very closely those of actual flight. Ultimate failure took place after the deflection was slightly over 1", and the spar then sustained a load equivalent to a factor of 2 in the Euler formula, the lower chord alone being taken as a column of the length of a drag bay. The failure shown by Fig. 1 (3) is typical for this kind of spar, that is, a sidewise deflection occurred of the lower chord only at a point near the center of the span.

Near the points of greatest bending moment, approximately the center of span of the continuously loaded upper spar under consideration, where the lower chord is of larger cross-section, and is nearer to the gravity axis than is the upper chord, the stress intensity in the lower chord due to side load only is less than in the upper chord (for stresses within the yield point). However, bending produces compression in the lower chord at this point, and the end load is also compressive, thus the total intensity is less than for a symmetrical spar. For the upper chord the bending stress is tensile which the compression end load tends to neutralize, and in average cases for single bay airplanes the net stress in the upper chord near mid-span approches zero.

Similarly it can be shown that for the lower spars of a multi-bay airplane in which the net tensile stresses may be large, with a shifting of the gravity axis in such a direction as to relieve the spar as a compression member for the condition of inverted flight, also reduces the tensile maxima for normal flight.

It is beyond the scope of this note to discuss the redistribution of stress intensity in a spar loaded beyond the yield point of the material, but it may be remarked that the yield point is by no means coincident with ultimate strength as has been sometimes assumed. For instance, in a spar combining camber with shifting of the gravity axis and subjected simultaneously to end load and side load in a constant proportion, the loads released, and the permanent set, if any, noted for each load increment; if a permanent set equal to 5% of the maximum deflection at the instant of failure is taken as indicating that the yield point has been passed, it will be found that the corresponding loads must be increased by 40% to 50% before failure occurs.

When wing panels are hinged to each other or to the cabane instead of being continuous, and the connecting pin is central, or if it has any position where no end load exists, the bending moment in the spar is nearly zero at the pin and much larger over the mid-span portions. Where there is an appreciable end load it is generally advisable to place this connecting pin in a position eccentric to the gravity axis, and nearer to that chord which is most stressed by the combined load, that is, nearer the upper chord of an upper spar, or nearer the lower chord of the lower spar of a biplane. It will at once be seen that when such a spar is compressed through truss action this position of the pin produces a bending moment of the same kind as would have existed were the spar continuous over the support under consideration. Usually the amount of such a moment is under complete control, as in the conditions of greatest stress when a moment equivalent to that due to full continuity is usually obtainable by locating the pin somewhere between the gravity axis and the appropriate chord. Such an eccentric position of the pin permits of smaller variations in the cross-sectional area of the spar chords in order to economically proportion them to sustain the stresses than would otherwise be possible.

If the tips of a biplane's wings are unsymmetrical in plan form, one spar having a longer overhang than the other, and it is desired for the sake of appearance to have the outboard bay of the same length for both front and rear spars, the line of action of the lift wires for the spar having the longer tip overhang should intersect the spar axis beyond its meeting with the line of action of the outboard lift strut, and for the spar having the shorter tip overhang the lift wire should intersect the spar axis within its intersection with the outboard lift strut, thus maintaining the same ratio of end moment to center moment for each of the spars in the outer bay, provided there is enough load in the outboard lift struts.

A somewhat different but conspicuously advantageous application of this principle of eccentric connections to balance stresses may be found in the conventional land type landing gear. A common arrangement consists of a pair of struts forming a V on each side of the fuselage or of the wing roots extending therefrom, to the apex of which is attached the axle whether of straight or bent form. This is shown diagrammatically in side view by Fig. 5 - (3) - the dotted lines indicating the position of wheel and axle at rest, and the full lines their position when the shock absorber at S is fully extended. Not infrequently the front strut inclines downwardly and forwardly, and so much in a recent design that the rear strut whether in a 3-point landing, or catapult launching, or even in a level landing unless the wheel's resistance to rolling exceeds one-fifth of its vertical reaction, is under tension and by its connection to the front strut causes bending therein. The rubber shock absorbers were secured near the apex of the V and vertically under the axle. This caused further bending of the front strut in the same direction as before, with the result that four-fifths of the strut cross-section is required to resist bending, and only one-fifth to perform its really necessary function as a strut.

By arranging the axle guides in front of the front strut and the points of attachment of the shock absorbers somewhat further forward, the maximum bending of the struts under any of the landing conditions may be reduced to 35% or so of the former arrangement with a corresponding saving of weight in the parts affected (Fig. 5) - (4).

In Fig. 5 - (5) is shown in front view, and (6) in side view another arrangement of the landing gear. In these diagrams the dotted lines show the position of the parts at rest, and the full lines their position when the shock absorbers are extended. The shock absorbers at S have been moved to a location at the top of the front strut and within the lower wing, this strut being restrained at the top only by the rubber, and at the bottom by a pin connection to a simple fitting which enclosed the axle. This fitting is connected to the rear strut by a universal joint of limited movement, while similar universal joints connect the upper ends of the rear strut to the rear wing spar, and the bent axle to the fuselage center. In this arrangement all bending moment at the V apex, and at the upper end of the rear strut, have been eliminated, except a small frictional effect, and with a little care the rubber shock absorbers may be attached to the upper end of the front strut so as to obviate bending there under maximum loads.

Under such conditions the landing gear struts may obviously be built much lighter in weight and of smaller diameter, the latter resulting in a reduction of head resistance.

Further elements of weight saving are available through provision in connecting the principal members together for realizing their full strength, as shown in Fig. 4. Part (16) of this figure shows a section through the joint of two tubes made by inserting into the smaller tube a ring with an annular depression similar to that of (14), and then by telescoping it into a larger tube outside of which is a narrow ring as shown in (15). The outer ring is then compressed with the two tubes into the depression of the inner fitting.

Fig. 4 (18) shows the exterior, and (17) a section through a lug fitting and the end of a tube, the fitting and ring before compression having about the proportions of (14) and (15). Such connections properly proportioned, develop the full strength of the tube in compression, in tension or in bending, and when failure occurs it is definitely remote from the joint.

By forming the inner fitting to a polygonal cross-section as shown in (20), and by compressing a tube and an external ring (19) around it to the same polygonal form, a joint is produced which is as shown in (21) - 100% efficient in torsion.

Joints of this type are not limited in production to very ductile material, as might be supposed, but are readily produced in material having a specified tensile elongation of 4% in 2" merely through appropriate relations between the thickness of the tube, the curvature of the fillets and the depth of the annular depression, and between the diameter of the tube and the length of the ring. The tube inner fitting and ring of sections 16 and 17 have been turned upon each other before photographing in order that their shadows might show clearly the construction; actually such a cut shows no joint unless magnified to 20 or more diameters.

The ball head bolt and drag wire strap (Fig. 3), in addition to the points already mentioned, are also of interest in that the deep cupping of the strap causes the line of action of the wire to intersect the bolt axis at its bearing on the spar. Tests have shown this combination at ultimate load to fail by shearing of the bolt without perceptible bending, indicating an elimination of a bending moment rather frequently found in spars at the drag wire connections.

Reference so far has been made to certain characteristic effects of arrangement which in particular cases result in enabling the use of lighter weight members to support a given load, and to other particular cases in which the loading itself may be modified to advantage by a suitable design of the parts, and to still other cases wherein by the elimination of material both results may be simultaneously accomplished.

These particular cases are by no means the only ones to which such methods may reasonably be applied; they merely illustrate the general fact that throughout every part and detail of a framed structure there is opportunity for design upon the same principles, and if the design is so applied through each and every detail the accumulated savings of weight may reach a surprising total. As an illustration, the bare structural frames only of the F4C-1 airplanes now approaching completion, exclusive of covering, of equipment or its containers, of power and its accessories, weigh less than one-half of the corresponding parts of the TS airplane, its prototype, and the TS is an excellent example of refined light weight construction along the lines considered practicable for wood. That this weight-saving has been accomplished without sacrifice of necessary strength, is evinced by the fact that the various detail tests required by the Navy have been successfully met.

The relative weights are exhibited in some details in Table I.

Weight of Structure

Wing Group

Upper and Outboard Lower Wing Panels	F4C-1 lb.	TS lb.
Ribs, complete	15.114	31.69
Spars, front	17.7760	25.00
Spars, rear	16.6987	24.00
Fittings, internal	1.3649	12.93
Leading edge	2.1848	2.41

Weight of Structure (contd.)

Wing Group

Upper and Outboard Lower Wing Panels	F4C-1 lb.		TS lb.	
Trailing edge	1.0589		.48	
Outer ends	.5668		2.39	
Brace wires	3.772		3.34	
Drag struts	3.0123			
Blocks and bracing	3.2051		4.26	
Bolts, nuts, etc.	1.7662		4.31	
Fittings, external	.6945	67.2142	1.21	112.02
Lower Center Wing Panel				
Ribs, complete	6.315		8.49	
Spars, front	.8257		3.28	
Spars, rear	.7622		3.30	
Fittings, internal	2.625		8.72	
Leading edge	.22			
Trailing odgo	.21			
Bolts, nuts, etc.	.5444		7.9[illegible]	
Struts	.884		3.75	
Sidewalk	3.1146	15.5009	13.12	48.56

Weight of Structure (Cont.)

Wing Group

Ailerons	F4C-1 lb.		TS lb.	
Ribs, complete	1.3692		2.7	
Spars	3.3918		5.6	
Edges	3.0432		1.39	
Blocks	.8106		.916	
Fittings	1.8792		1.31	
Brace wires	0.0	10.4940	1.15	13.066
Interplane Struts and Wires				
Wires	1.0313		9.48	
Struts (without fairing)	20.963		58.5	
Bolts, nuts, etc.	.5444	22.5387	4.3	72.28
Total Wing Group	115.7478 lb.= 47.07%		245.926 lb.= 100%	

Tail Group

Stabilizer and Elevator	F4C-1 lb.	TS lb.
Ribs	3.816	3.73
Spars, front	2.989	5.86
Spars, rear		3.5
Leading edge	1.259	.74
Trailing edge	1.2994	.42
Blocks	.7184	1.26
Fittings	.7754	2.99

Weight of Structure (Cont.

Tail Group

Stabilizer and Elevator	F4C-1 lb.		TS lb.	
Brace wires	2.044		3.42	
Bolts, nuts, etc.	.322		.66	
Horns	.344	13.5672= 58.99%	.42	23.00 = 100%
Fin and Rudder				
Ribs	1.7918		1.31	
Spars, front	1.3129		1.77	
Spars, rear			1.13	
Leading edge	.518		.26	
Trailing edge	.4423		.42	
Blocks and bracing	.163		.48	
Fittings	.4765		1.88	
Brace wires	.516		.42	
Bolts, nuts, etc	.1329		.55	
Horns	.125	5.4784= 64.22%	.31	8.53 = 100%
Body Group				
Longerons	7.0559		21.3	
Stays	8.9634		8.00	
Wires	.9056		23.00	
Engine supports	1.9086		3.5	
Fittings	6.5165		11.2	

Weight of Structure (Contd.)

Tail Group

Body Group	F4C-1 lb.	TS lb.
Bolts, nuts, etc.	included	4.8
Engine bed	3.9070	8.0
Stern post	.4817	1.0
	29.7387= 36.8%	80.8= 100%
Total Frame Weight	164.5322 lb.= 46.2%	358.256 lb.= 100%

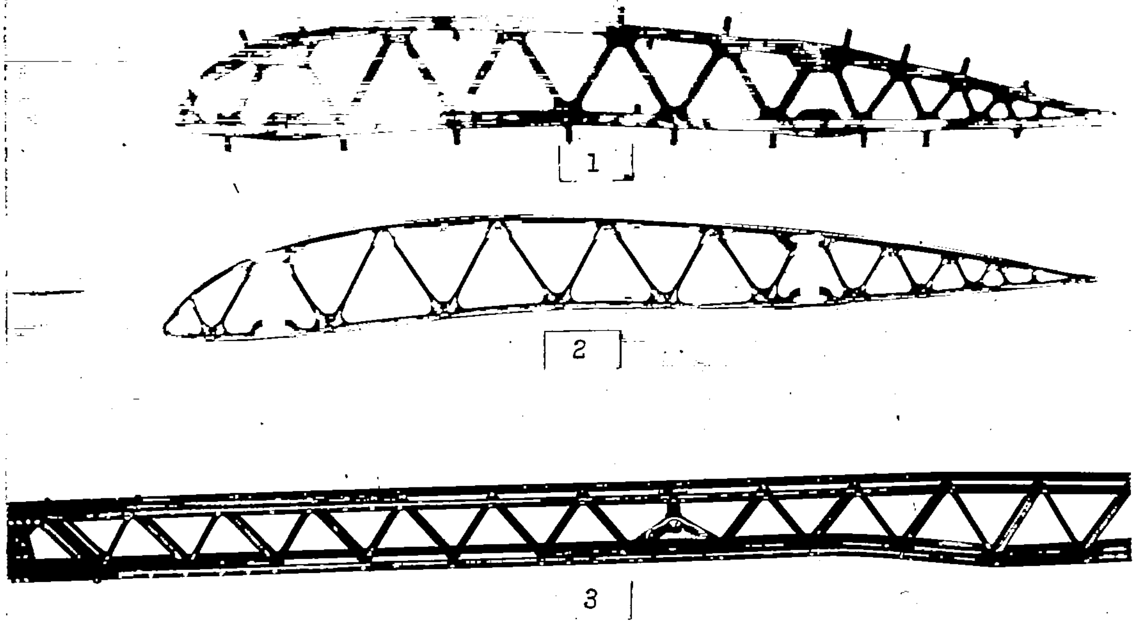

Fig. 1

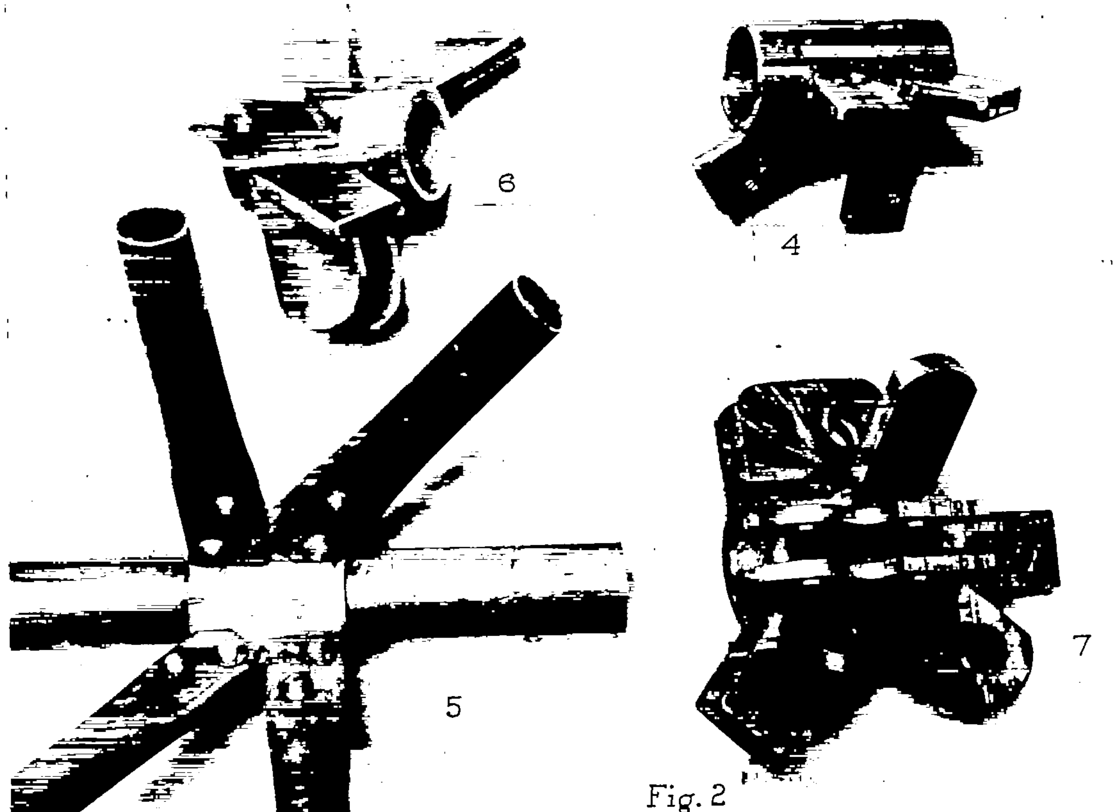

Fig. 2

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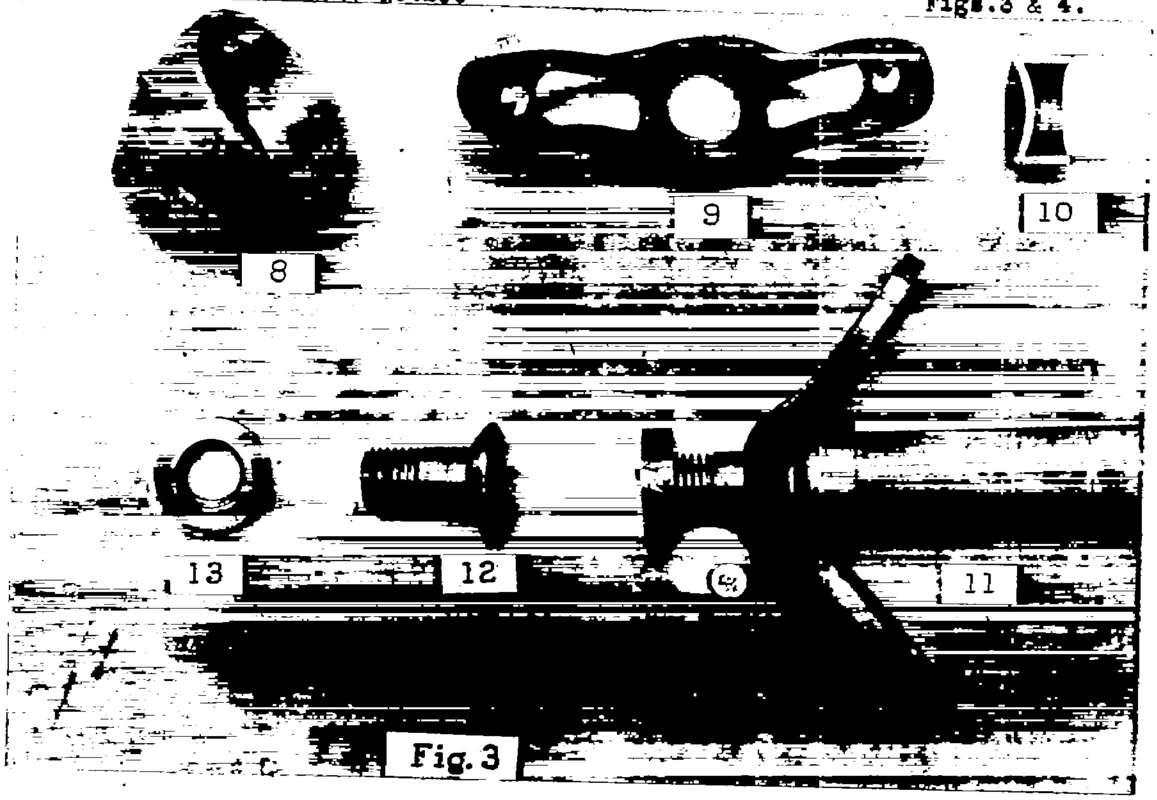

Fig. 3

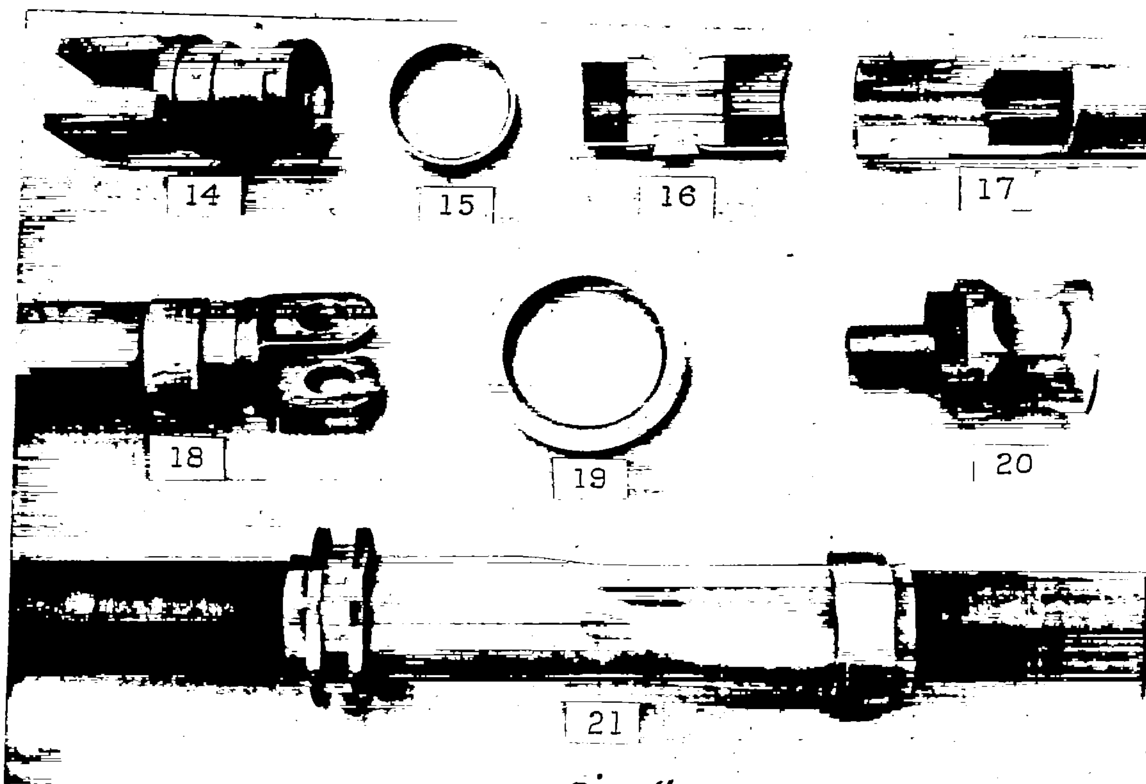

Fig. 4.

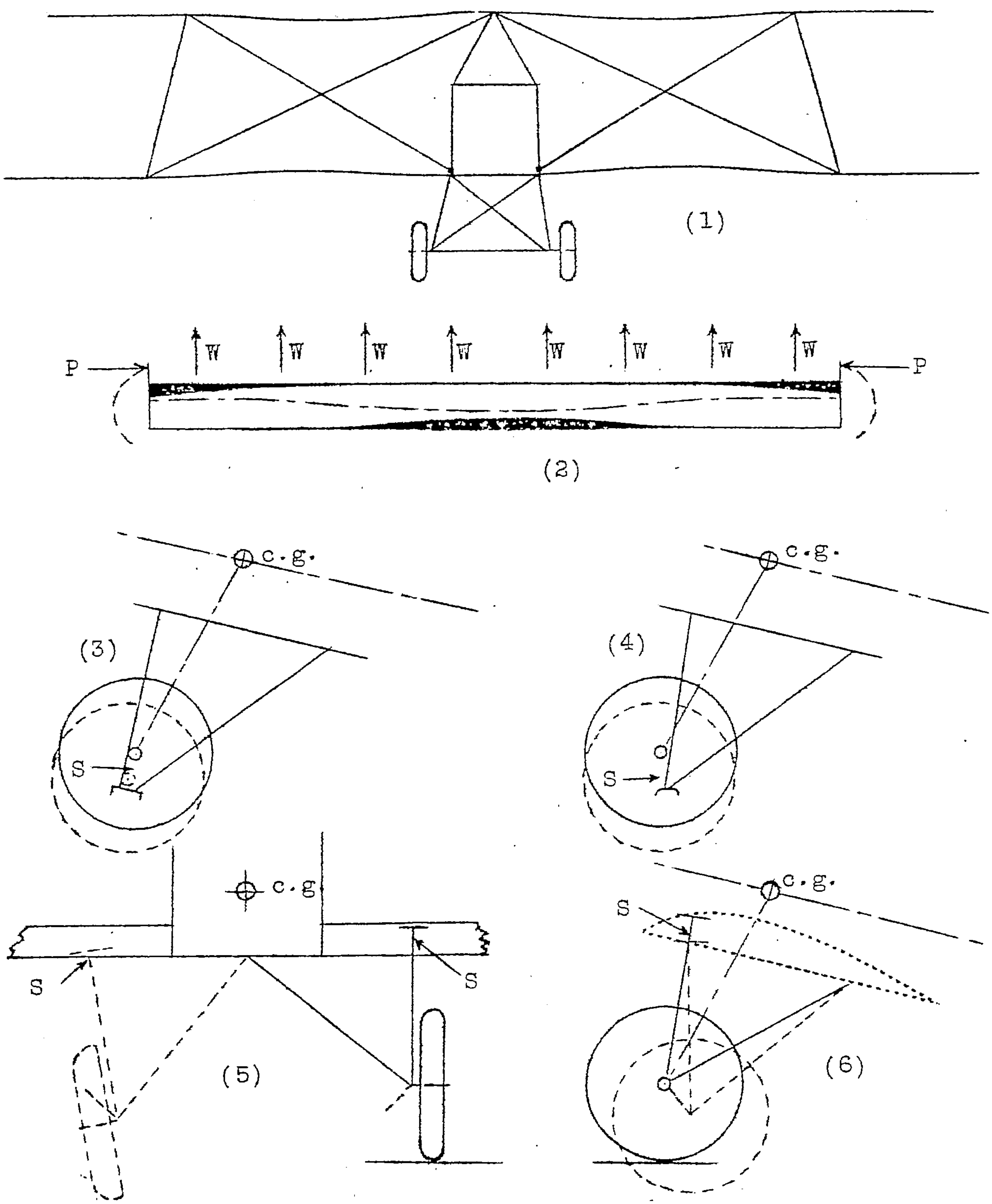

Fig. 5